Homogeneous evolution of overcontact massive binaries resulting in BH+BH mergers

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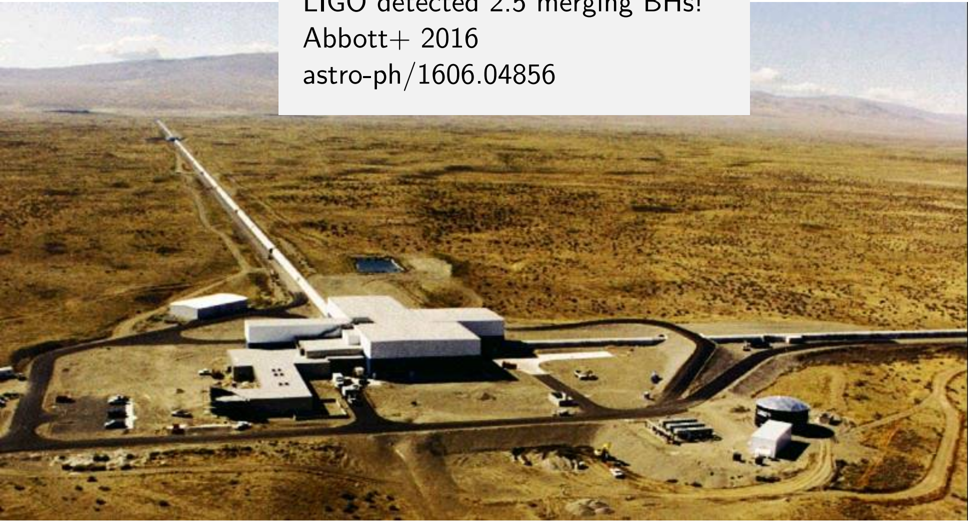
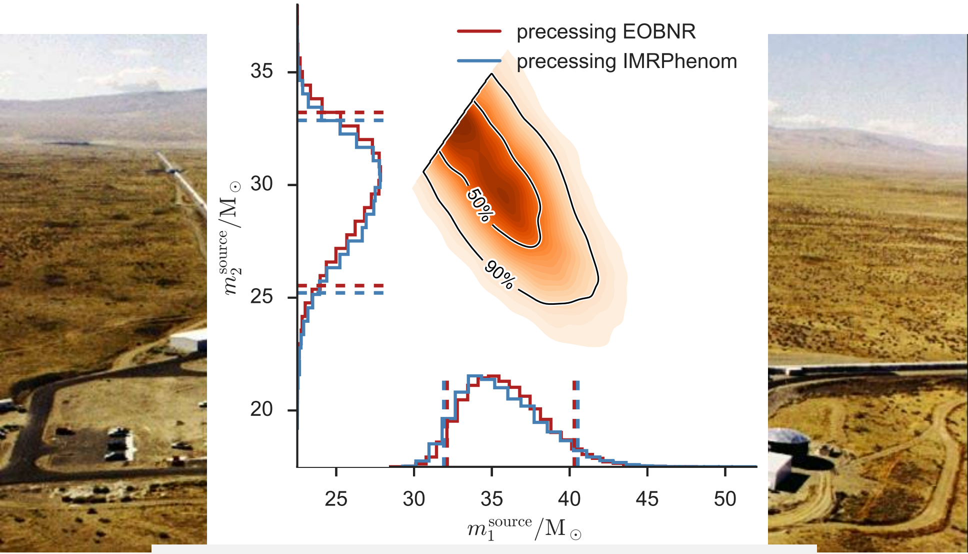
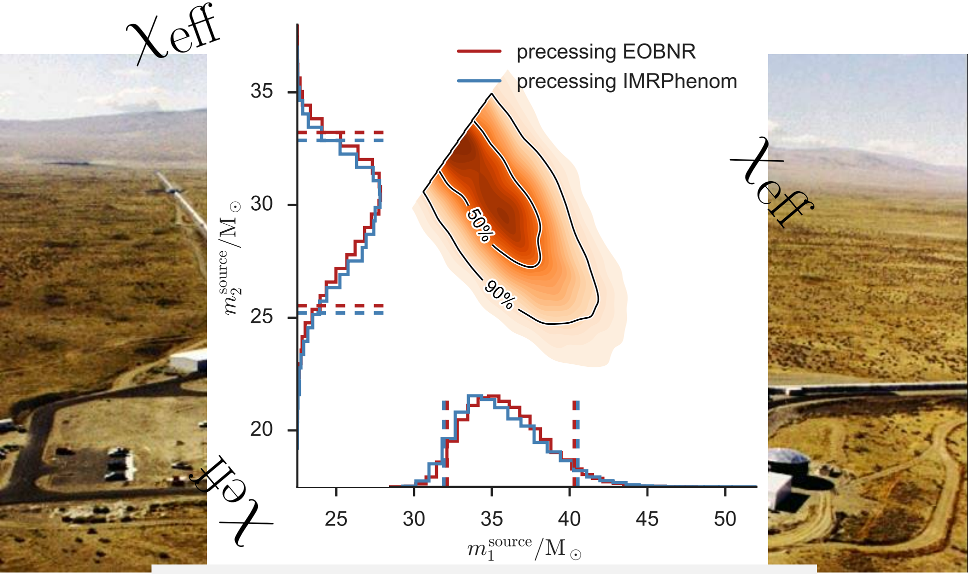
Argelander-Institut für Astronomie

First science run of advanced LIGO detected 2.5 merging BHs!
Abbott+ 2016
astro-ph/1606.04856

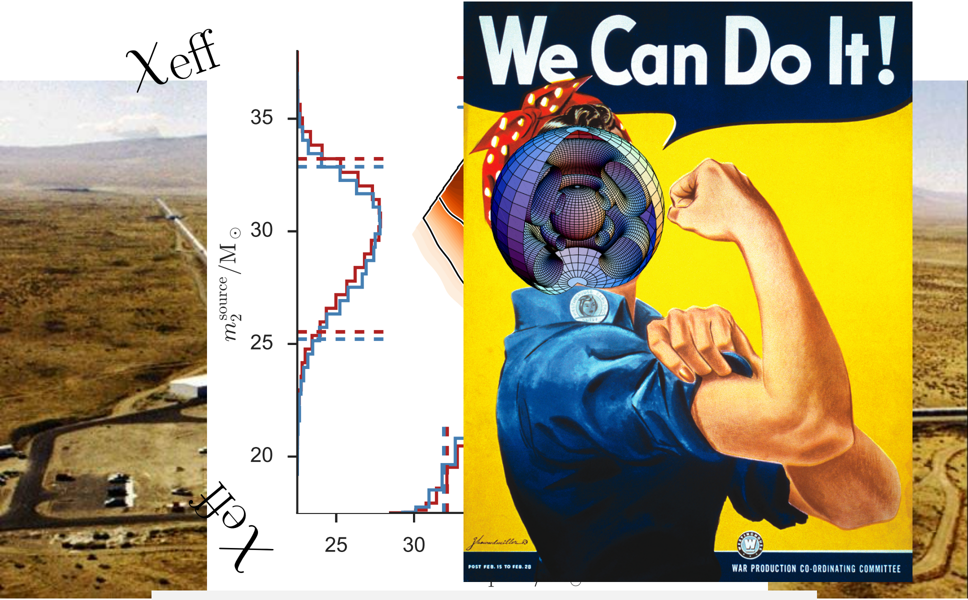




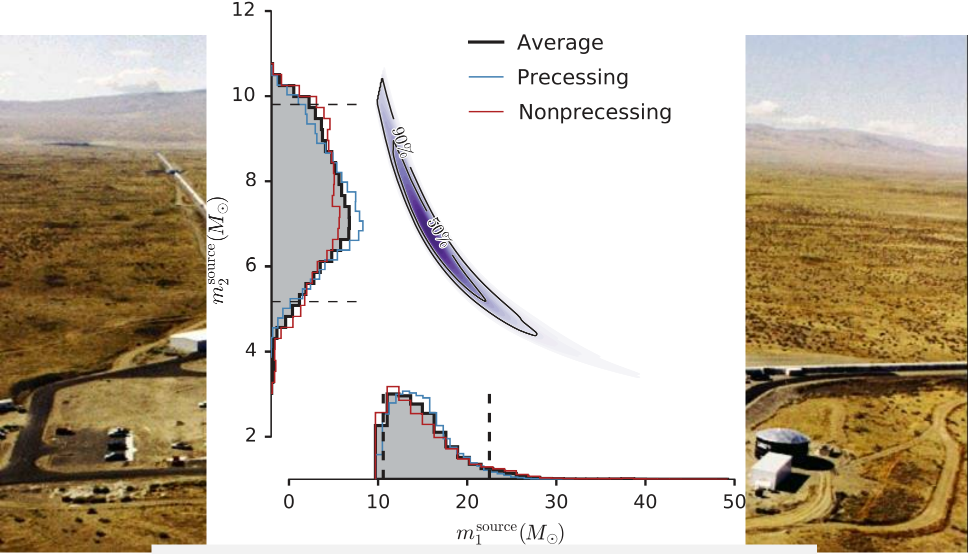
GW150914, Abbott+ 2016 , astro-ph/1606.01210



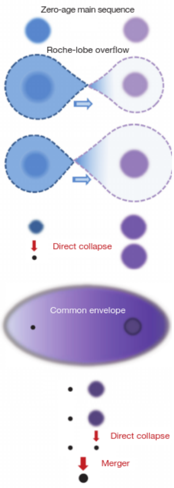
GW150914, Abbott+ 2016 , astro-ph/1606.01210



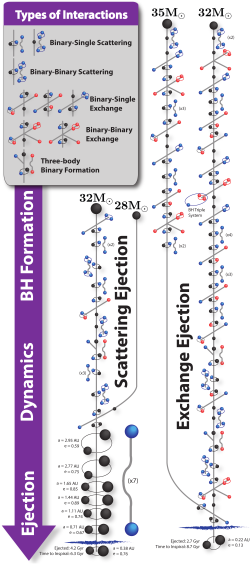
GW150914, Abbott+ 2016 , astro-ph/1606.01210



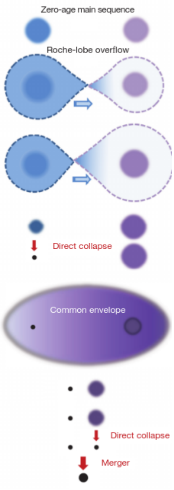
GW151226, Abbott+ 2016 , astro-ph/1606.04855

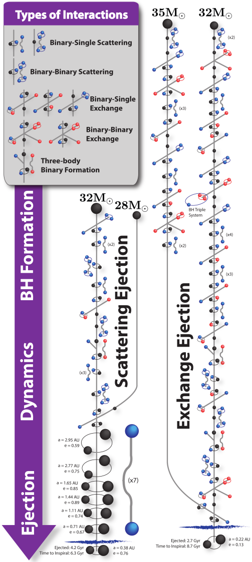


Field, Belczynski et al. (2016)
astro-ph/1602.04531



Cluster, Rodriguez et al. (2016)
astro-ph/1604.04254





Field, Belczynski et al. (2016)
astro-ph/1602.04531

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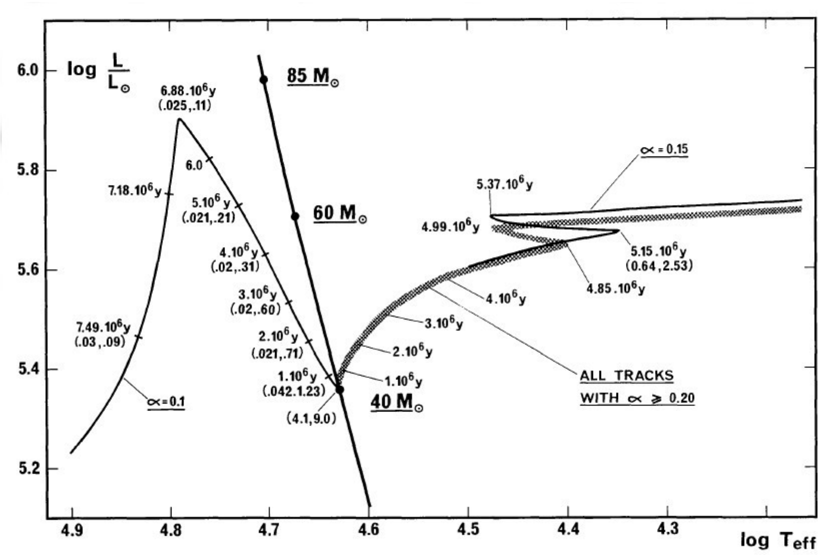
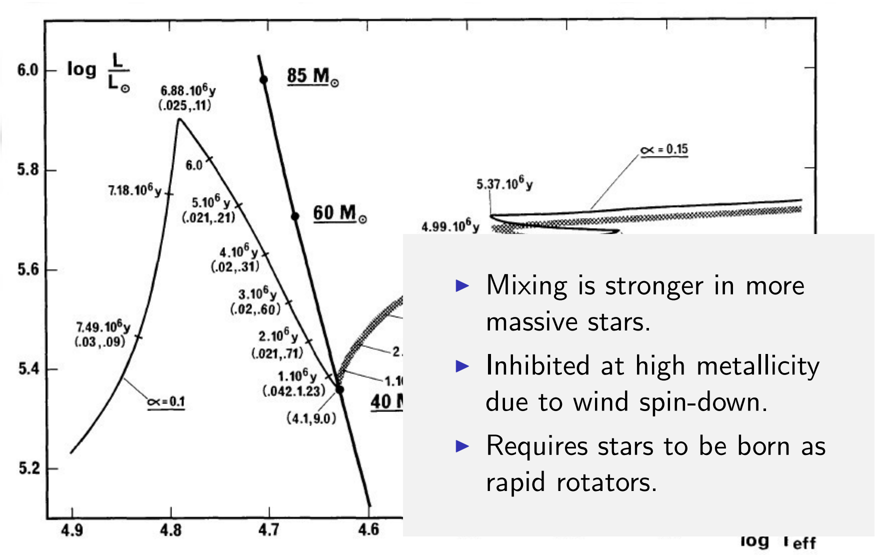
astro-ph/1604.04254

Chemically homogeneous evolution (Maeder 1987)



Chemically homogeneous evolution (Maeder 1987)



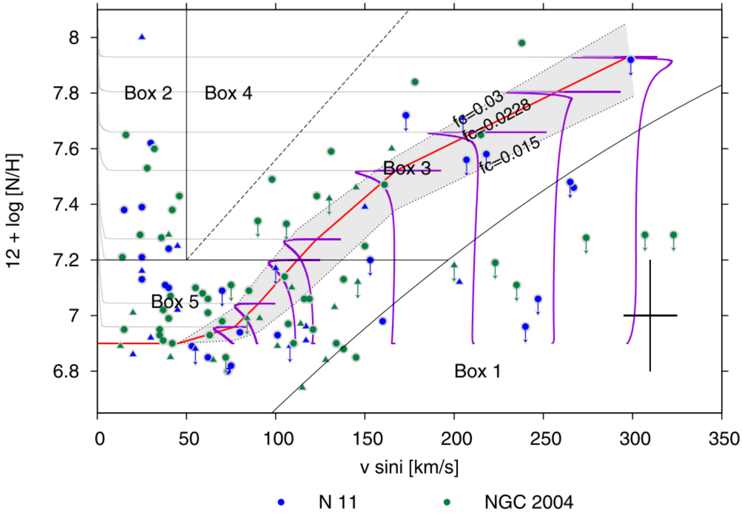
- Mixing is stronger in more massive stars.
- Inhibited at high metallicity due to wind spin-down.
- Requires stars to be born as rapid rotators.

Rotation and CNO surface enrichment

Flames survey, Hunter+ 2009/Stellar models, Brott+ 2011

Heger+ 2000

$D = f_c \sum_i D_{i,\mathrm{rot}}$



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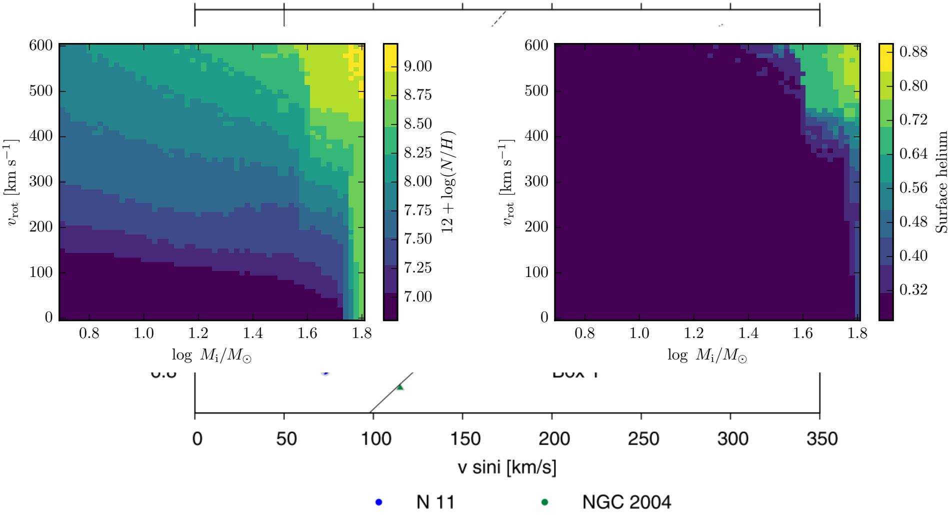
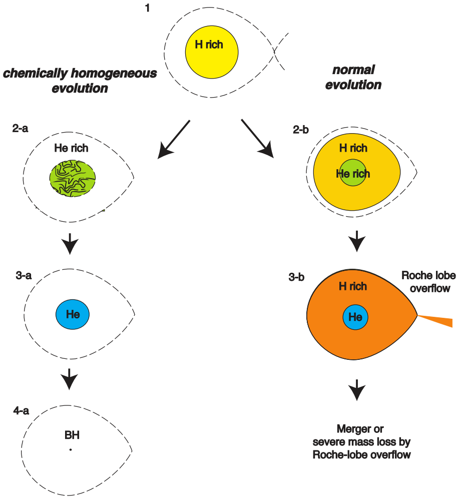


Case M evolution, de Mink 2009



Mandel & de Mink 2016

- Possibility of double-BH formation.
- Königsberger et al. 2014: Double He star system in the SMC
  - $M_1 = 66M_\odot$, $M_2 = 61M_\odot$
  - $P = 19.3$ days

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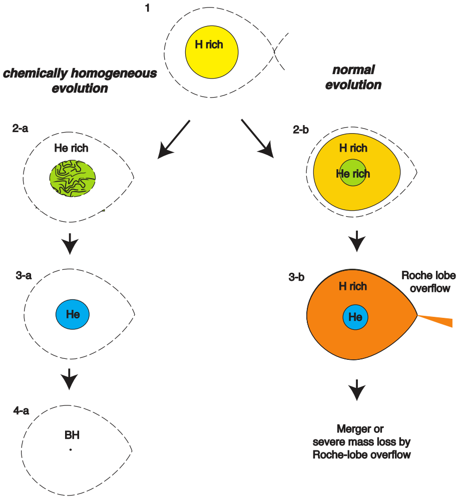

Mandel & de Mink 2016

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Song+ 2016

de Mink & Mandel 2016

Marchant+ 2016

Königsberger et al. 2014, HD5980

Table 6
Orbital Solutions for *Stars A* and *B*

Element	N v 4944 RVs		System A+B
	Star A	Star B	
$M \sin^3 i$ ($M_\odot$)	61 (10)	66 (10)	127 (14)
$a \sin i$ ($R_\odot$)	78 (3)	73 (3)	151 (4)
K (km s^{-1})	214 (6)	200 (6)	...
e	...	...	0.27 (0.02)
ω_{per} (deg)	...	...	134 (4)
V_0 (km s^{-1})	...	...	131 (3)
P_{calc} (days)	...	...	19.2656 (0.0009)

Table 7
Orbital Solution for *Star C*

Element	Current Analysis	Schweickhardt (2000)
P_C (days)	96.56 (0.01)	96.5
T_{peri} (HJD)	2451183.40 (0.22)	2451183.3
e	0.815 (0.020)	0.82
ω (deg)	252 (3.3)	248
K (km s^{-1})	81 (4)	76

Königsberger et al. 2014, HD5980

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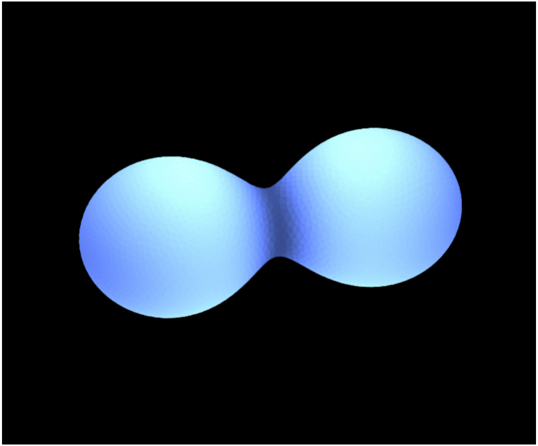
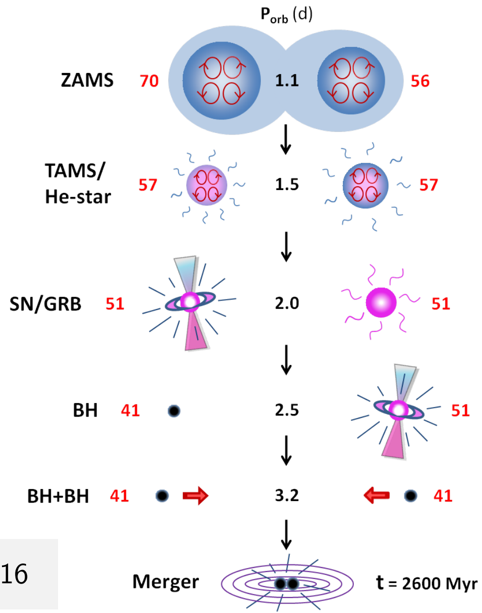
$$P_C/P_{A+B} = 5.0089$$

Almeida et al. 2015: Massive overcontact binary

$M_1 \simeq M_2 \simeq 30 M_\odot$, $q = M_1/M_2 = 1.008$, $P_{\rm orb} = 1.12$ [d]



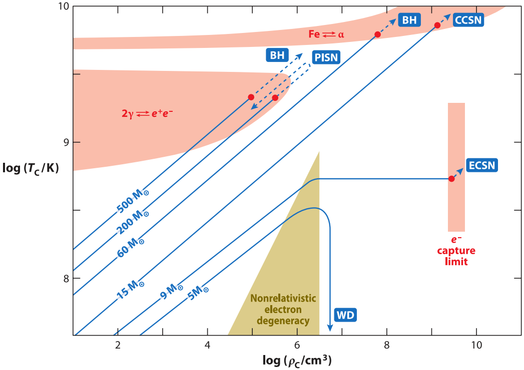
VFTS 352, most massive overcontact binary known.



Marchant+ 2016

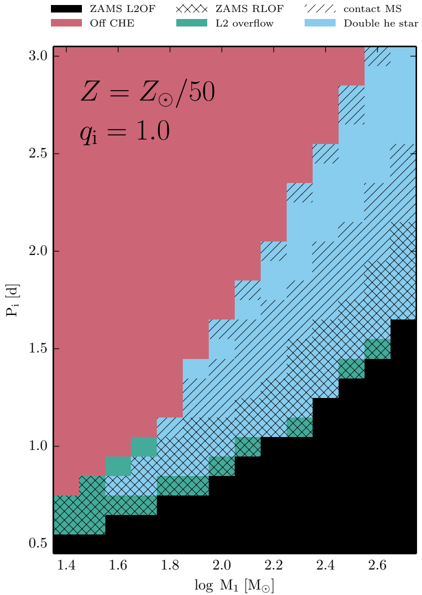
Pair-instability supernovae, LGRBs

Langer 2012



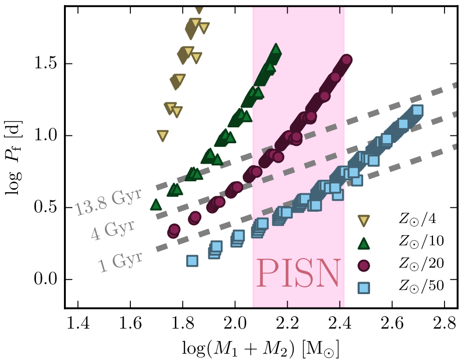
For helium stars, full disruption from explosion for final masses $M \sim 60 - 130 M_{\odot}$. Heger & Woosley 2002

- Additionally, formation of high spin BH+accretion disk can result in LGRBs (Woosley 1993, Yoon & Langer 2005)

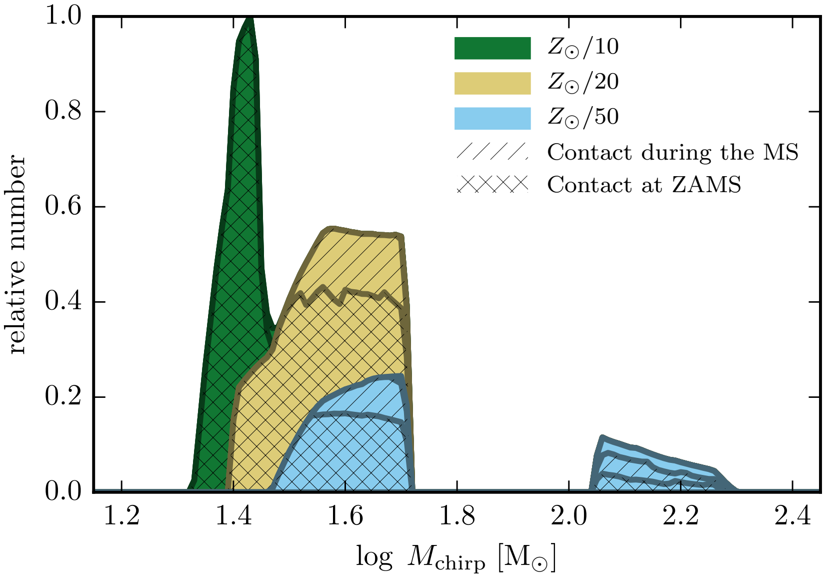


Marchant+ 2016

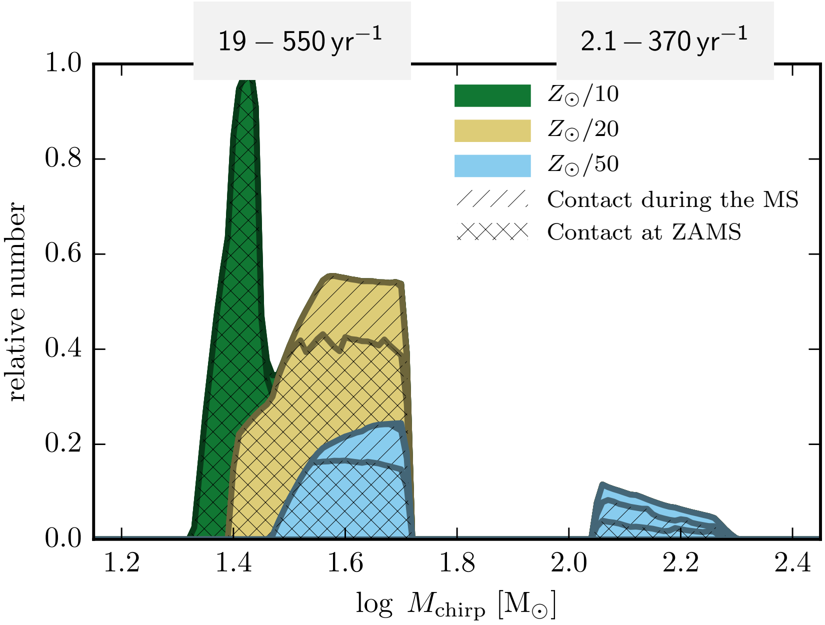
- Black hole mergers with mass ratio very close to 1
- Gap in chirp masses due to PISNe
- For $Z < Z_\odot/20$ LGRBs could be produced



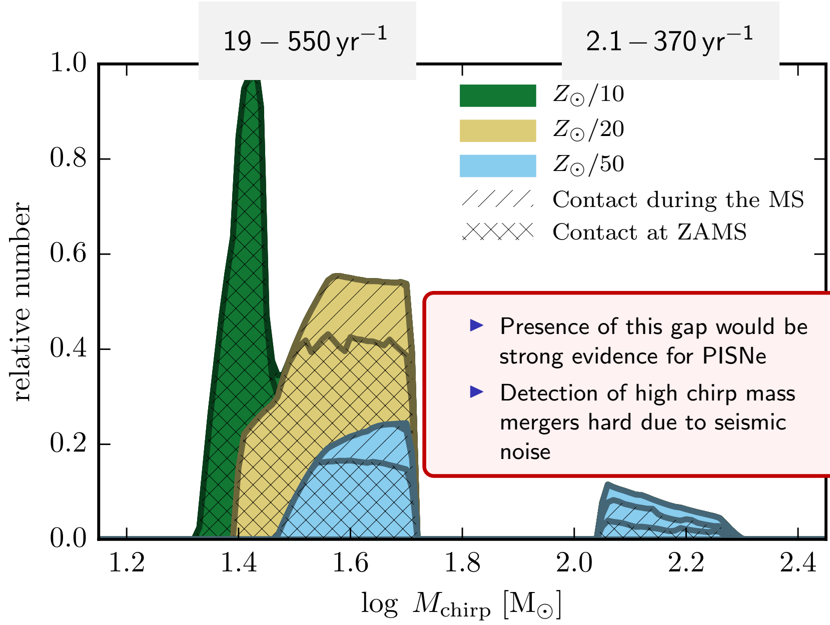
Chirp mass distribution



Chirp mass distribution



Chirp mass distribution



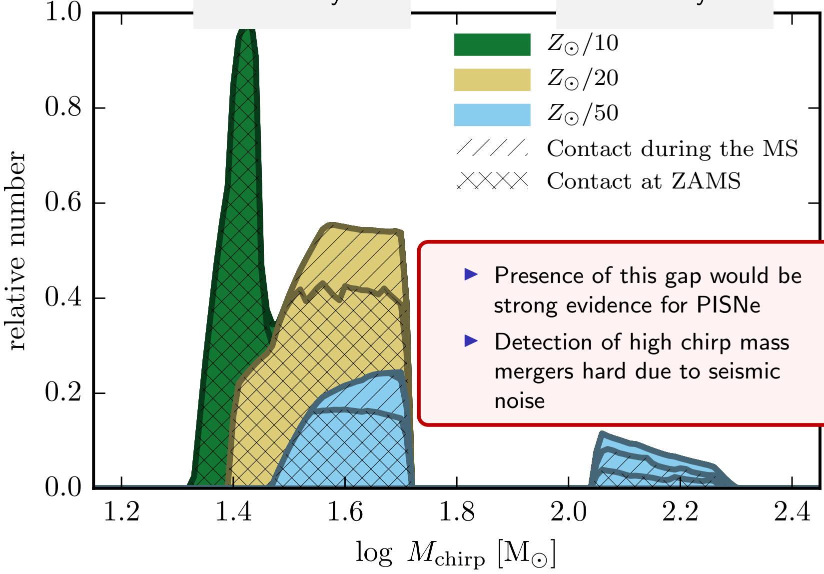
- Presence of this gap would be strong evidence for PISNe
- Detection of high chirp mass mergers hard due to seismic noise

Chirp mass di

de Mink & Mandel (2016): 470 yr^{-1} (0 – 1500)

$19 - 550\,yr^{-1}$

$2.1 - 370\,yr^{-1}$



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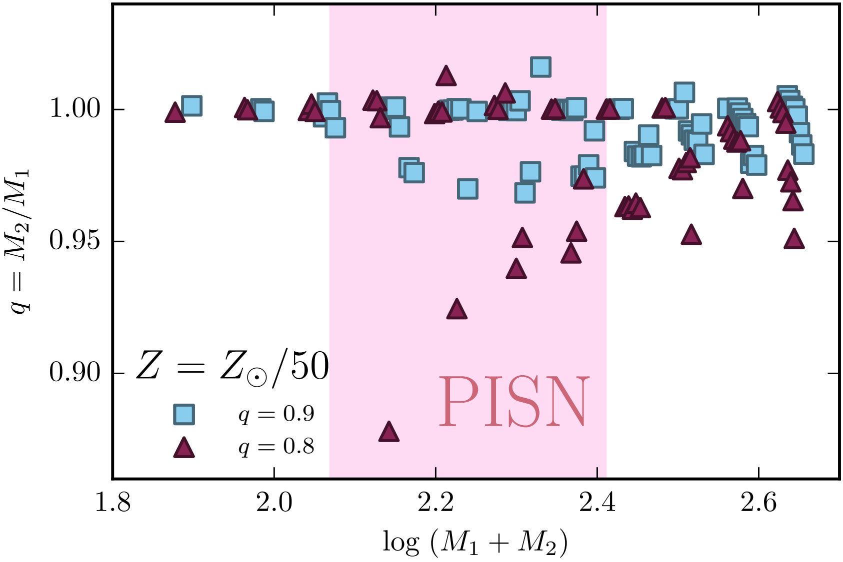
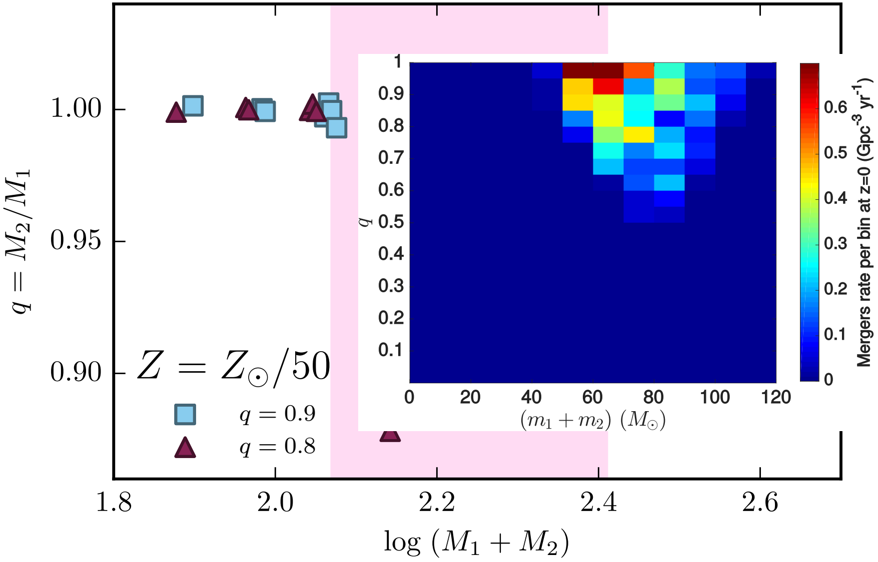
Mass ratios

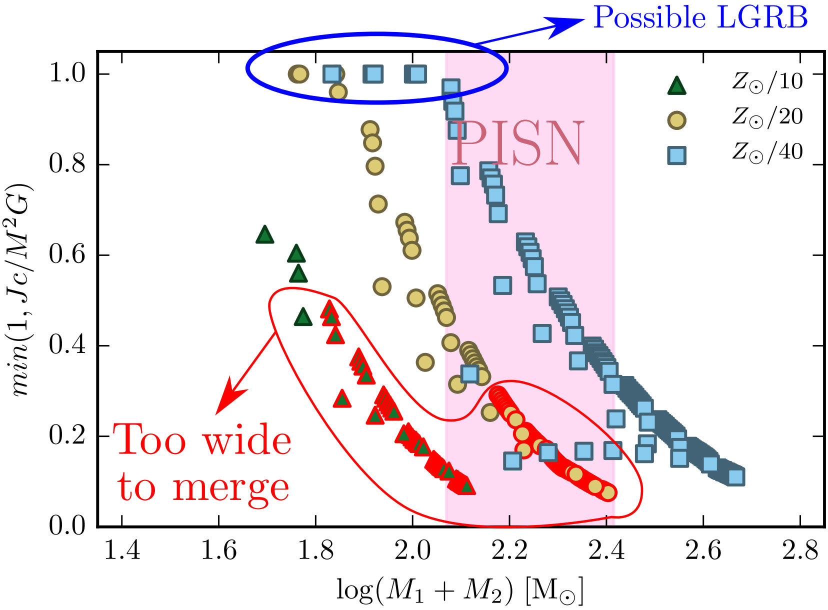


Mass ratios



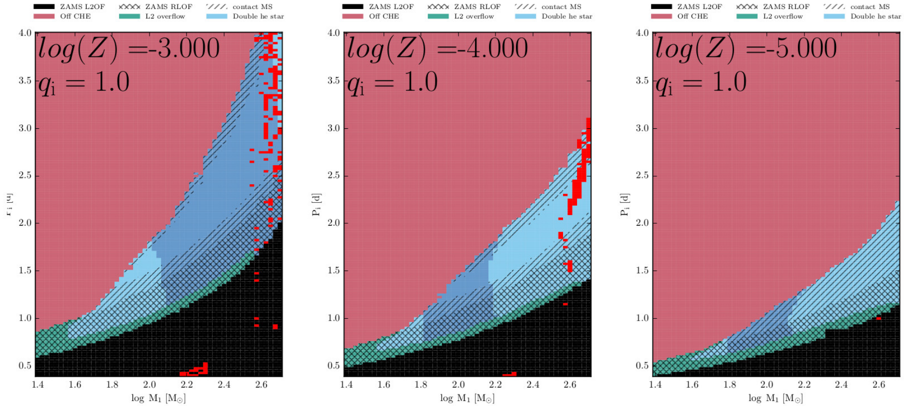
$q = M_2/M_1$
1.00
0.95
0.90
$Z = Z_\odot/50$
$q = 0.9$
$q = 0.8$
1.8
2.0
2.2
2.4
2.6
$\log\,(M_1 + M_2)$
q
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
40
60
80
100
120
$(m_1 + m_2)\ (M_\odot)$
Mergers rate per bin at z=0 (Gpc^{-3} yr^{-1})
0.6
0.5
0.4
0.3
0.2
0.1
0

Final BH spins and LGRBs

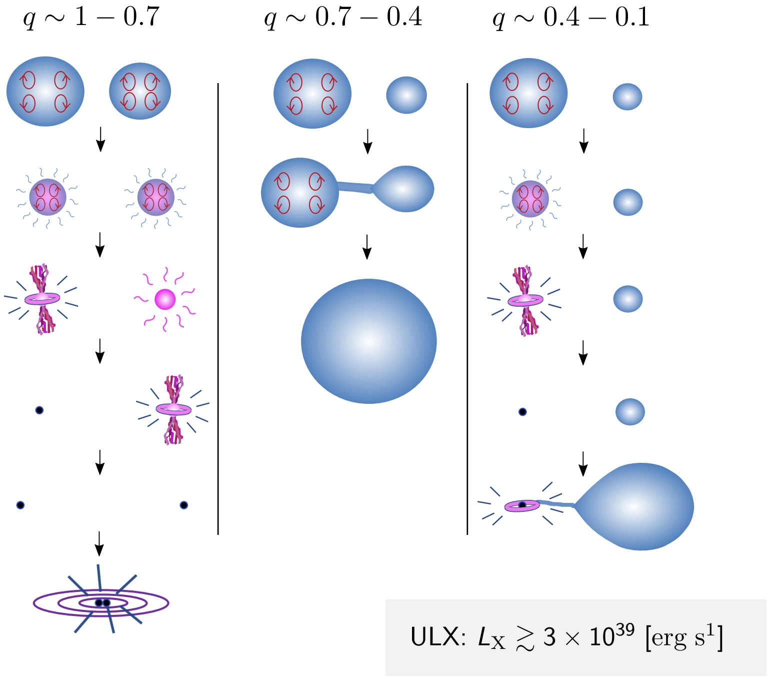


What about lower metallicities?

du Buisson+ in preparation

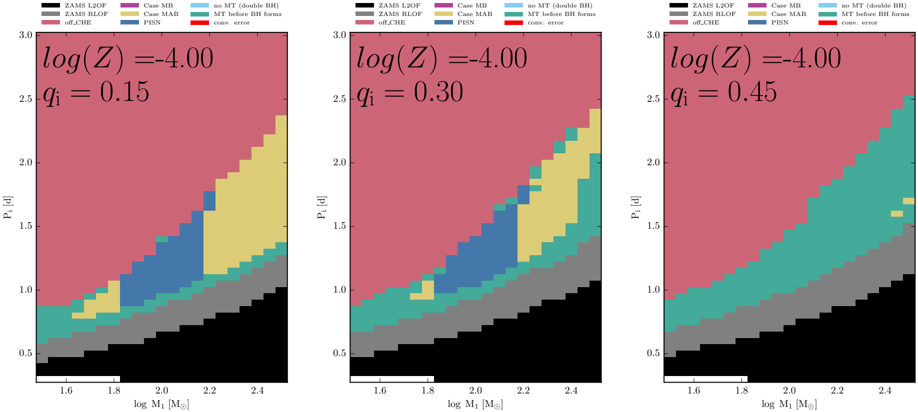


For POP III, τ_{GW} of order Myrs. MS merger!


$q \sim 1 - 0.7$
$q \sim 0.7 - 0.4$
$q \sim 0.4 - 0.1$
ULX: $L_{\rm X} \gtrsim 3 \times 10^{39}$ [erg s^{1}]

Formation of ULXs with CHE

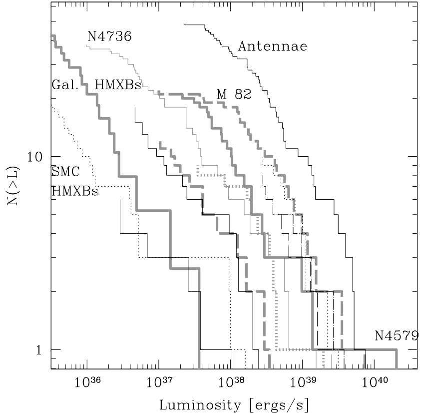
ie. what about smaller mass ratios?



Marchant+ in preparation

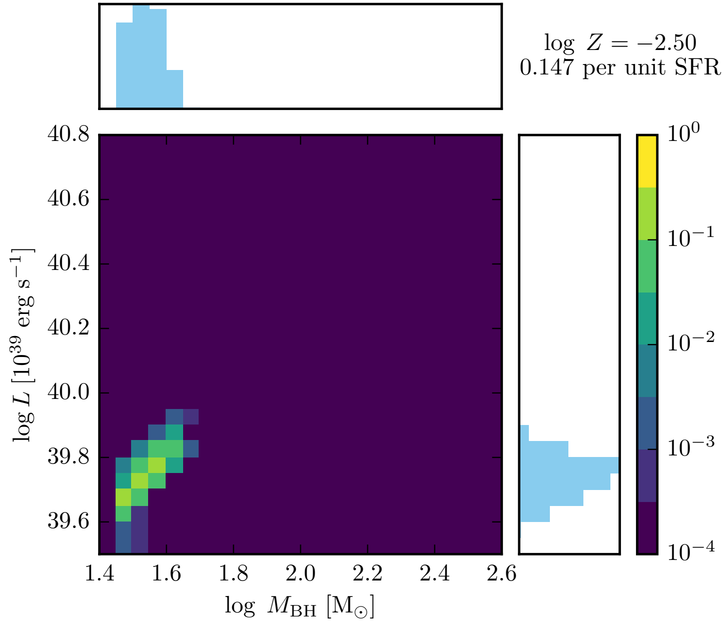
Grimm et al. 2002

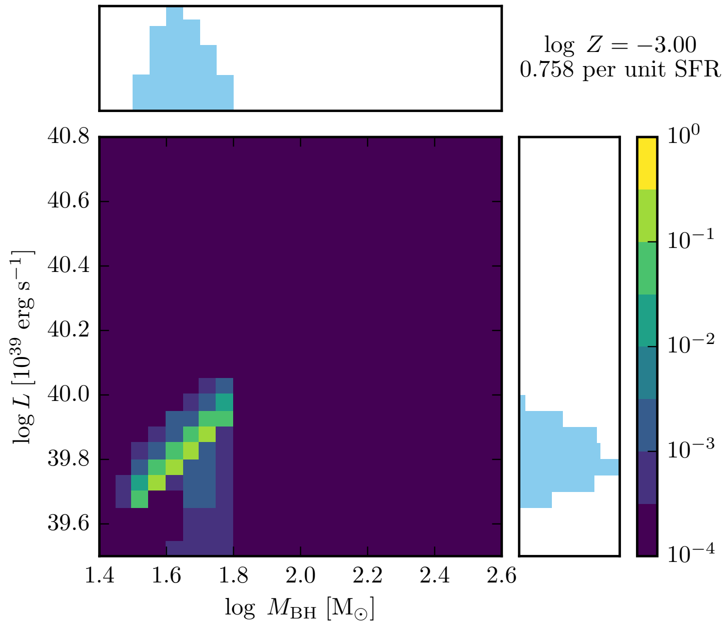
XRB luminosity function and star formation



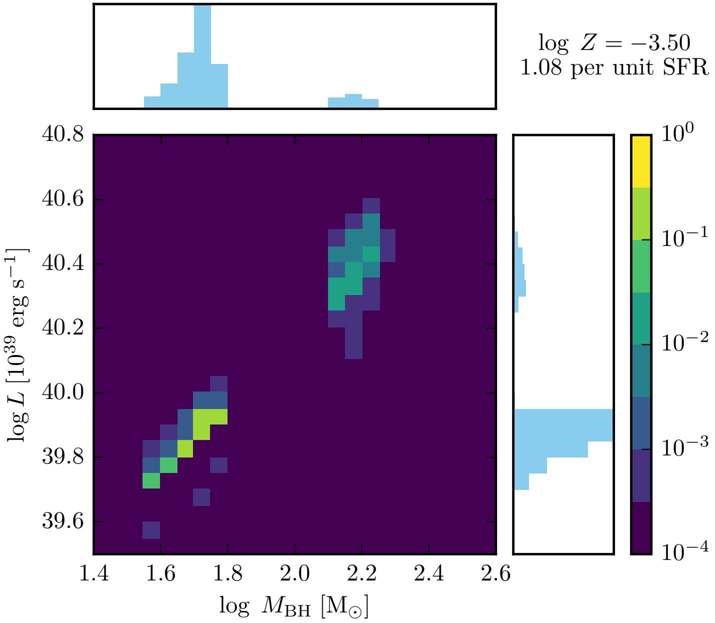
CHE should normally produce the most massive BHs for given conditions.

Resulting XRBs should be on the upper end of luminosity distribution.

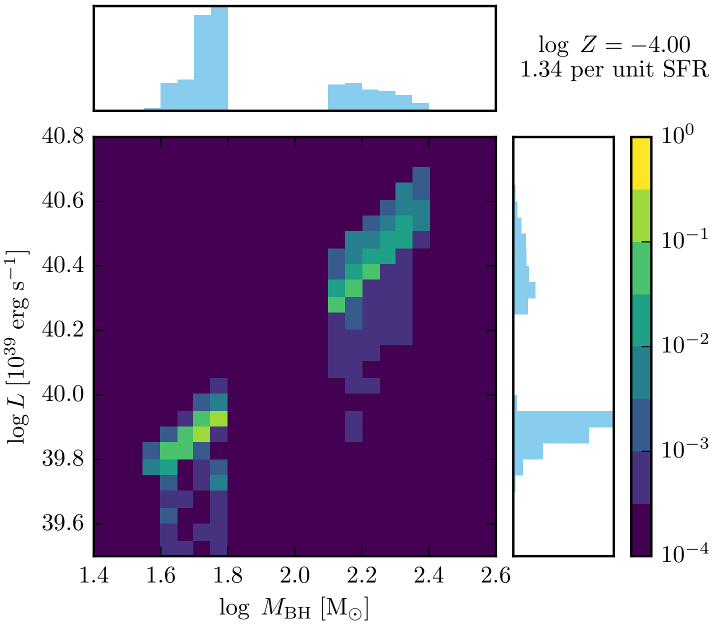

log $Z = -2.50$
0.147 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
$\log L\ [10^{39}\ \mathrm{erg\ s^{-1}}]$
1.4
1.6
1.8
2.0
2.2
2.4
2.6
$\log\ M_{\rm BH}\ [\mathrm{M_\odot}]$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}



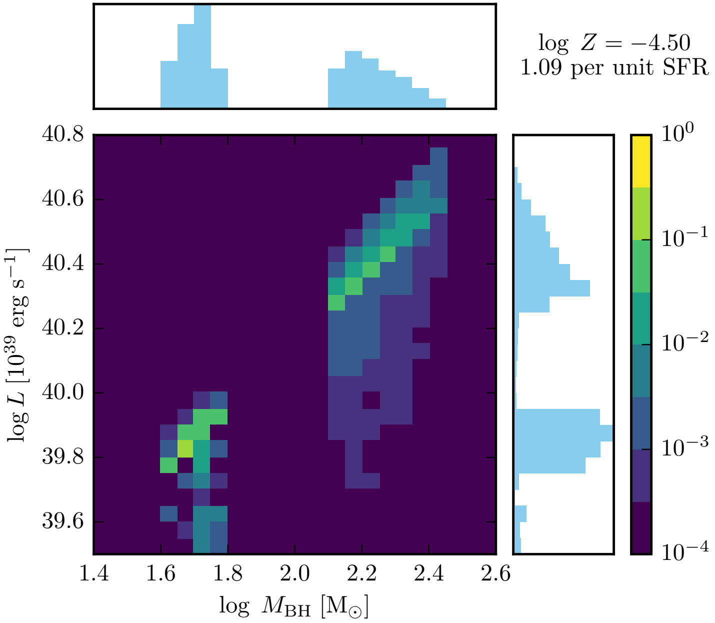
log $Z = -3.00$
0.758 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
log L [10^{39} erg s^{-1}]
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [M$_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



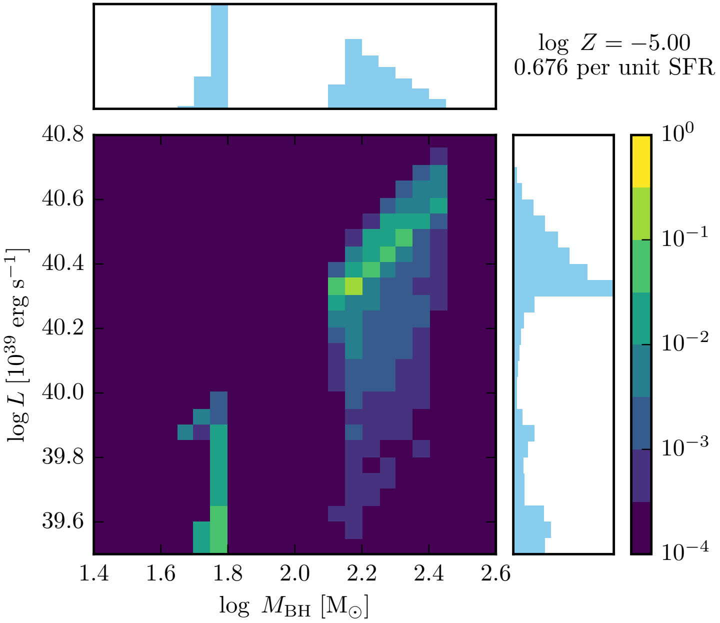
log $Z = -3.50$
1.08 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
log L [10^{39} erg s^{-1}]
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [M$_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



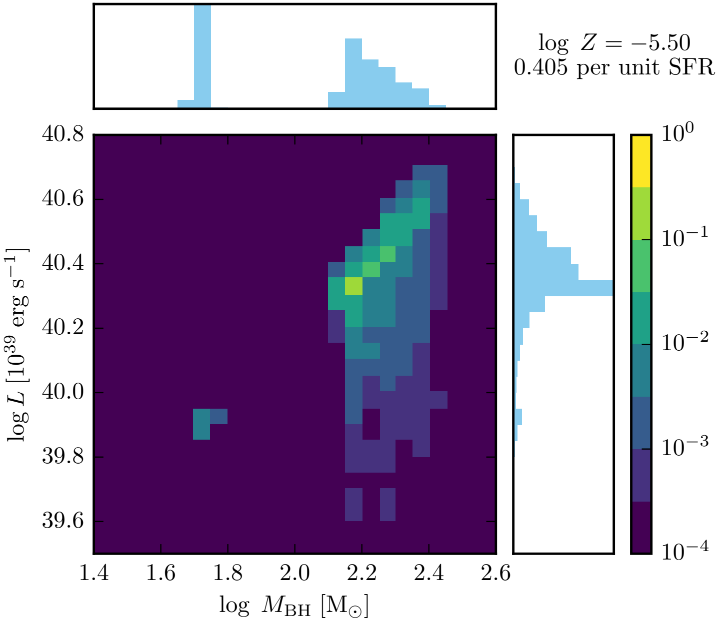
log $Z = -4.00$
1.34 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
log L [10^{39} erg s^{-1}]
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [$M_\odot$]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}



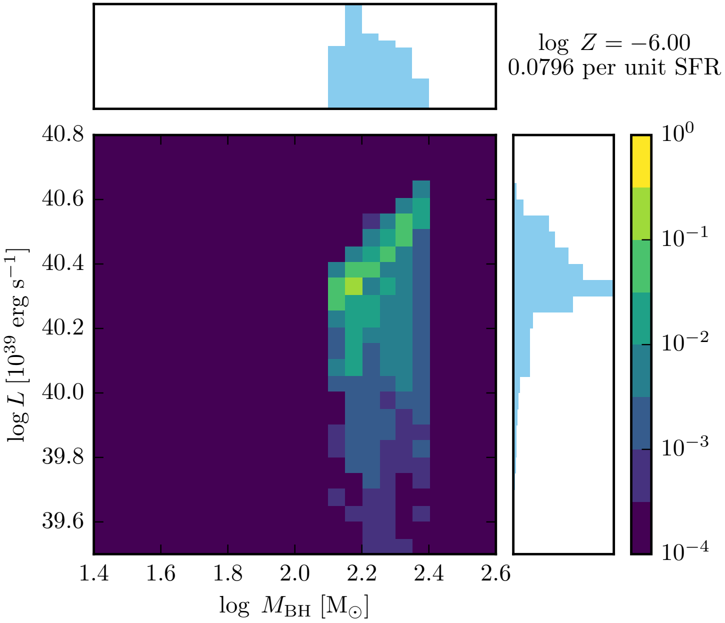
log $Z = -4.50$
1.09 per unit SFR
log L [10^{39} erg s^{-1}]
log $M_{\rm BH}$ [M$_\odot$]
40.8
40.6
40.4
40.2
40.0
39.8
39.6
1.4
1.6
1.8
2.0
2.2
2.4
2.6
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



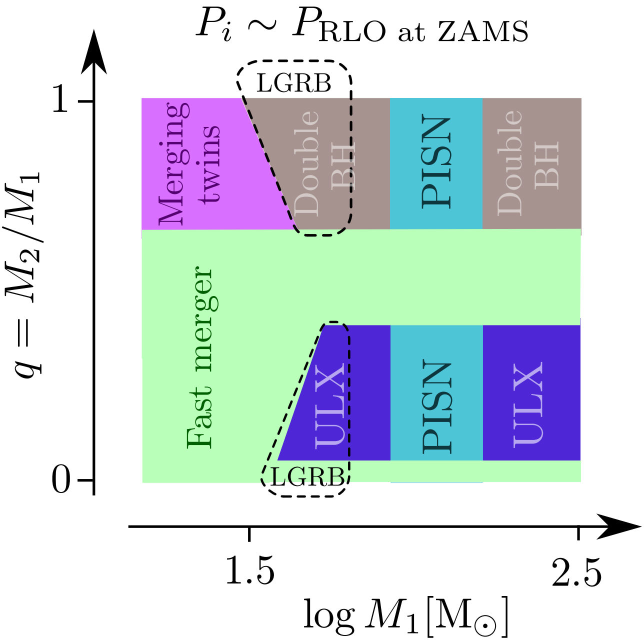
log $Z = -5.00$
0.676 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
log L [10^{39} erg s^{-1}]
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [$M_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



log $Z = -5.50$
0.405 per unit SFR
40.8
40.6
40.4
40.2
40.0
39.8
39.6
log L [10^{39} erg s^{-1}]
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [M$_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

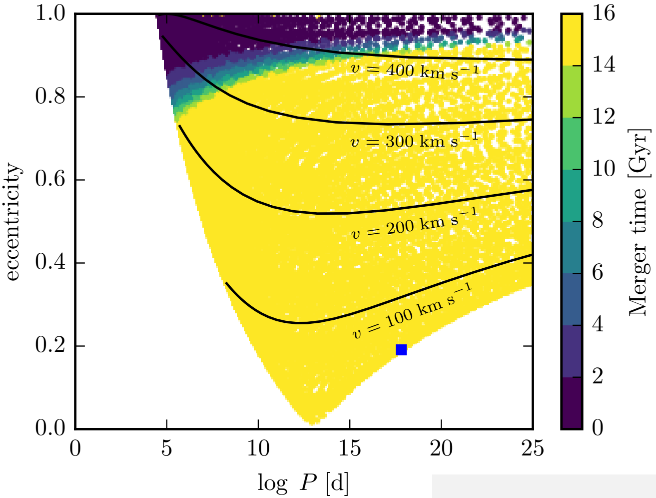


log $Z = -6.00$
0.0796 per unit SFR
log L [10^{39} erg s^{-1}]
40.8
40.6
40.4
40.2
40.0
39.8
39.6
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log $M_{\rm BH}$ [M$_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}


$P_i \sim P_{\rm RLO\ at\ ZAMS}$
LGRB
Merging twins
Double BH
PISN
Double BH
Fast merger
ULX
PISN
ULX
LGRB
1
0
$q = M_2/M_1$
1.5
2.5
$\log M_1 [\rm M_\odot]$

From a ULX to a merging NS+BH binary

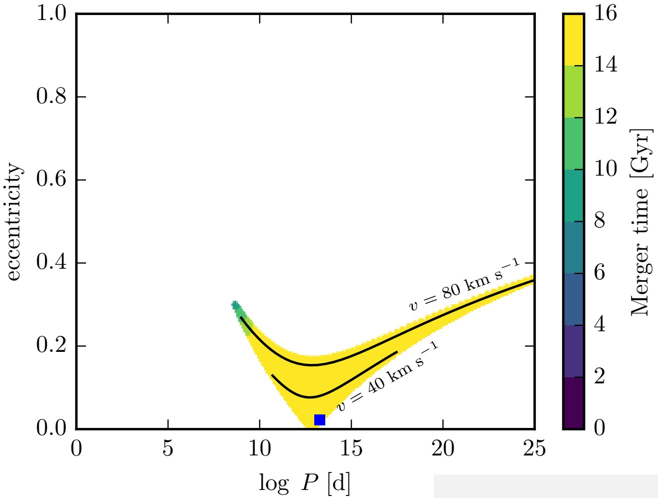
Example: $Z = 3 \times 10^{-4}$, $M_{\rm BH} = 56.4 M_\odot$, $M_2 = 12.4 M_\odot$, $P = 11.9[\rm d]$
$\rightarrow M_{\rm NS} = 1.4 M_\odot$ + kick (Maxwellian, $\sigma = 265\ \rm km\ s^{-1}$)



$f_{\rm merge} = 6.5\%$, $f_{\rm disrupt} = 59\%$

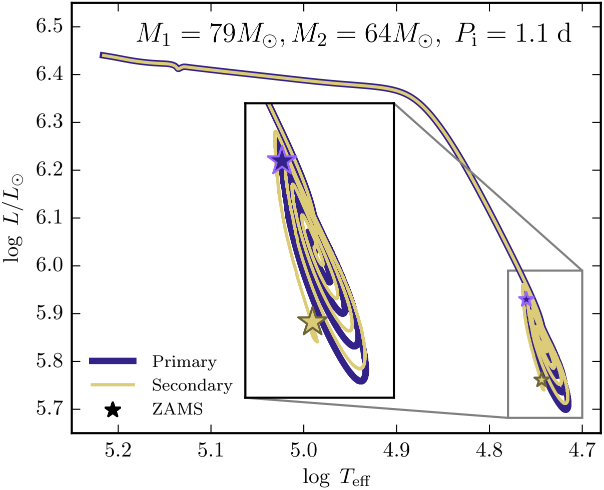
From a ULX to a merging BH+BH binary

Example: $Z = 3 \times 10^{-4}$, $M_{\rm BH} = 136 M_\odot$, $M_2 = 49 M_\odot$, $P = 12.7[\rm d]$
$\rightarrow M_{\rm NS} = 45 M_\odot$ + kick (Maxwellian, $\sigma = 26.5~\rm km~s^{-1}$)



$f_{\rm merge} = 0.3\%$, $f_{\rm disrupt} = 0\%$

Contact "synchronizes" a binary



- Lifetimes of order Myrs
- But both stars deplete He within 100-1000 yrs

Conclusions

- Chemically homogeneous evolution in very massive binaries provides a common channel for LGRBs, PISNe, ULXs and merging double BHs.
- Detection of a gap in measured chirp masses of merging BHs could provide strong evidence por PISNe (and also on PPISNe).
- At low metallicity, BHs with high spin could be produced resulting in LGRBs through the collapsar model.
- Synchronization of the binary components can result in both stars ending their lives within a timescale of a few 100 yrs.
- Future observations by aLIGO and other facilities will provide strong constraints on this model. If seismic noise remains too high to detect $M_{\mathrm{chirp}} > 100 M_{\odot}$, might need to wait for eLISA, ET.

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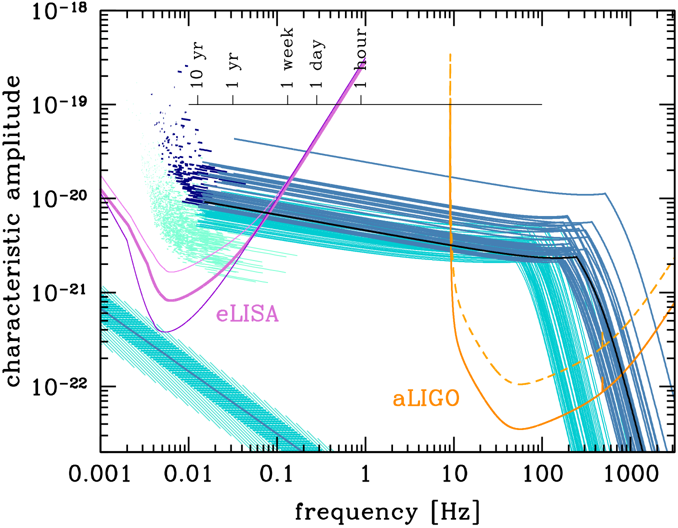

characteristic amplitude
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
frequency [Hz]
0.001
0.01
0.1
1
10
100
1000
10 yr
1 yr
1 week
1 day
1 hour
eLISA
aLIGO

Back-of-the-envelope rate estimates

$$R_{MWEG} = R_{SNe} \times f_{\mathrm{binary}} \times f_P \times f_q \times f_{\mathrm{IMF}} \times f_Z$$

- $R_{SNe} \sim 10^{-2}\ yr^{-1}$
- $f_{\mathrm{binary}} \sim 1/3$
- $f_P \sim 0.05$
- $f_q \sim 0.2$
- $f_{\mathrm{IMF}} \sim 0.05 - 0.01$ (above and below PISN gap)
- $f_Z \sim 0.1$

$$R_{MWEG} \sim 2 \times 10^{-7}\ [\mathrm{yr}^{-1}]; 3 \times 10^{-8}\ [\mathrm{yr}^{-1}]$$

aLIGO detection rates

Abadie et al. 2010:

$$N_{\rm gal} = \frac{4}{3}\,\pi\,\left(\frac{d_{\rm horizon}(M_{\rm chirp})}{\rm Mpc}\right)^3\,(2.26)^{-3}\,(0.0116)$$

- $d_{\rm horizon}(M_{\rm chirp})$: distance limit for detection ($\propto M_{chirp}^{15/6}$).
- $(2.26)^{-3}$: averaging due to relative inclinations and sky positions.
- $0.0116\ {\rm Mpc}^{-3}$: Extrapolated density of MWEGs (Kopparapu et al. 2008)

For a massive BH-BH merger with $M_{\rm BH} = 60\ M_\odot$ (or $130\ M_\odot$), we get $d_{\rm horizon} \simeq 10\ {\rm Gpc}$ (or $d_{\rm horizon} \simeq 19\ {\rm Gpc}$)

aLIGO detection rates

Z	$Z_\odot/50$	$Z_\odot/20$	$Z_\odot/10$	$Z_\odot/4$
dBH/SN $<$ PISN (10^{-3})	0.67	1.3	0.34	0
dBH/SN $>$ PISN (10^{-3})	0.27	0	0	0
LIGO rate [yr^{-1}] $<$ PISN	3539	5151	501	0
LIGO rate [yr^{-1}] $>$ PISN	5431	0	0	0

Table: Fraction of systems per SN that result in double BHs that would merge in less than $13.8\,\mathrm{Gyr}$ (upper 2 rows), and aLIGO detection rates (lower 2 rows), assuming that all galaxies have the corresponding metallicity, both above and below the PISN gap.

Rate Estimates: $19 - 550\,\mathrm{yr}^{-1}$ for BH-BH mergers below the PISN gap and of $2.1 - 370\,\mathrm{yr}^{-1}$ above the PISN gap.